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MORPHOLOGY OF DEFECTS AND THE RESIDUAL STRENGTH OF ALKALI-SILICATE AND QUARTZ GLASSES IMPACTED BY HIGH-VELOCITY METEORITES

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Previous work has shown that impacts by high-velocity micrometeorites decrease the initial strength of the quartz glass in spacecraft portholes by more than a factor of 2. The present work continues the search for criteria that would make it possible to evaluate indirectly but quite reliably the residual strength of the quartz glass according to the morphology of the defects formed.

Key words: residual strength, quartz glass, spacecraft portholes.

Prior to the present studies the residual strength of glass (RSG) was evaluated using a simplified but quite rough procedure based on the strength of the remaining undamaged layer of the glass neglecting the morphological particularities of defects and the presence of microcracks. In other words, the thickness of a defect was subtracted from the initial thickness of the glass and the body of the glass was regarded as being defect-free. Even the first studies showed that this approach to evaluating the RSG is too optimistic and does not comport with the established facts.

In a previous work [1] we performed very important studies and drew practical conclusions concerning the portholes in the International Space Station (ISS) that made it possible to formulate a direction and, in consequence, to evaluate the RSG for quartz glasses impacted by micrometeorites. It was found that the initial strength of glass drops unpredictable by a factor of 2 or more. It was determined that this sharp drop of the strength is explained by the fact that after an impact there appears a defect with a deep damaged layer whose depth is greater than in the case of "ground-based" defects, which are oriented into the interior of the glass. It was obvious that without additional detailed studies it is simply impossible to determine the danger of subsequent cracking of the glass due to a microcrack in the presence of static loads from the deformation of body and from air pressure in the inter-glass space which are present when the porthole is in use. For this reason we decided to search for criteria that would make it possible to evaluate the RSG level indirectly. Initially, we were interested in the relation between the RSG and the morphology of defects, specifically, the dimensions and number of the sub-zones of defects and the lengths of microcracks. To confirm this relation it was necessary to prove reasonably that the conclusions drawn and their dependences found for alkali-silicate and quartz glasses correlate well with one another.

In [1] we used primarily glass samples whose thickness and dimensions were considerably (several-fold) smaller than that of the actual glasses used. For this reason a decision was made to perform the studies on glass samples with real thickness and dimensions and to determine whether or not the scale factor affects the structure of a defect and the RSG under identical test conditions.

TEST CONDITIONS

Nine samples of Optiwhite alkali-silicate glass with thickness 15 mm and dimensions 300 × 300 mm (three samples for each of three impact loads) and natural quartz glass for a 254 mm in diameter and 14 mm thick porthole were used for the experiments.

The microparticle sizes and impact velocities in the experiments are presented in Table 1.

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TABLE 1. Test Conditions

Glass sample No.	Glass type	Particle diameter, mm	Particle mass, g	Impact velocity, km/sec	Impact angle, deg
1	Soda lime	0.2	0.00001 (computed)	7.13	0
2	Soda lime	0.2	0.00001 (computed)	7.06	0
3	Soda lime	0.2	0.00001 (computed)	7.15	0
4	Soda lime	0.4	0.00009	7.15	0
5	Soda lime	0.4	0.00009	7.05	0
6	Soda lime	0.4	0.00009	6.80	0
7	Soda lime	0.8	0.00077	7.11	0
8	Soda lime	0.8	0.00076	7.04	0
9	Soda lime	0.8	0.0074	7.09	0
10	Quartz	0.4	0.0009	7.06	0

RESULTS

Photographs of the defects appearing in glass samples are displayed in Fig. 1. The photographs were taken from the front and end. Comparing these photographs and those of glass containing defects [1] confirms that the character and morphology of the defects are practically identical. This made it possible to use the proposed method of evaluating the impact strength of the microparticles [1] according to the number and diameter of the sub-zones of defects to interpret the data obtained.

It is evident from Table 2 that the sub-zone diameters are relatively stable for the three identical impact conditions. This shows that the mechanism of defect formation for the same impact strength is stable. This allows us to switch with greater confidence in the tests results to the method used in subsequent studies where one sample per influential factor is used. As a result the studies can be performed more quickly and the resources needed to perform expensive tests and fabricate samples, especially, quartz glass, saved.

Curves of the subzone diameter versus impact strength are presented in Fig. 2. The same linear relation observed previously is seen for each subzone. For comparison, the dimensions of the subzones for quartz glass with the identical impact strength are presented on the left-hand side of the figure. The data obtained confirm the previous conclusion that the impact strength of silicate glasses is higher by a factor of 2 or more. This result is of great practical interest for designing new portholes. The use of multicomponent glass for portholes is even more desirable, since such glass can be strengthened by an order of magnitude compared with quartz glass, thereby increasing the micrometeorite impact stability of portholes.

TABLE 2. Failure Subzones of the Samples

Sample No.	Failure subzone with diameter, mm				
	Subzone No.				
	1	2	3	4	5
1	0.6	0.9	1.2	1.9	2.6
2	0.5	0.9	1.0	1.7	2.4
3	0.45	0.8	1.1	1.75	2.3
4	1.3	3.1	4.1	6.5	11.3
5	1.2	2.8	5.3	6.9	11.5
6	0.7	2.9	4.3	6.3	11.3
7	2.5	7.7	14.6	18.5	24.2
8	1.4	6.3	12.2	16.9	24.15
9	1.8	4.9	14.3	18.8	25.5

It is proposed in [1] that the dangerous microcracks are located in the third and fourth subzones of a defect. Analysis of the photographs taken of defects from the side confirmed this conclusion. It is evident that the microcracks are oriented into the interior volume of the glass and project beneath these subzones. Experience has shown that even a single microcrack is a dangerous source of cracking of glass under a static load. For now it is impossible to determine the failure mechanism of the glass in the presence of a bundle of such microcracks, since the existing method of measuring the coefficient of crack formation K_{1c} is based on the dynamics of only a single crack.

The depths of the defects and the sizes of the microcracks as functions of the impact strength and curves of the dependences (Fig. 3) are presented in Table 3.

The dependences obtained can be used to improve NASA's method, using the length of the initial microcrack multiplied by a correlation factor due to the number of microcracks to calculate the RSG. This factor can be determined only experimentally by comparing the strength indicators of glasses with one or more cracks for a large number of experiments.

The main method of evaluating the RSG must itself be the method used at the Scientific-Research Institute of Technical Glass (NIITS) and based on the construction of long-time strength curves.

An advantage of this method is that it is possible to calculate from the long-time strength curves the minimum life-

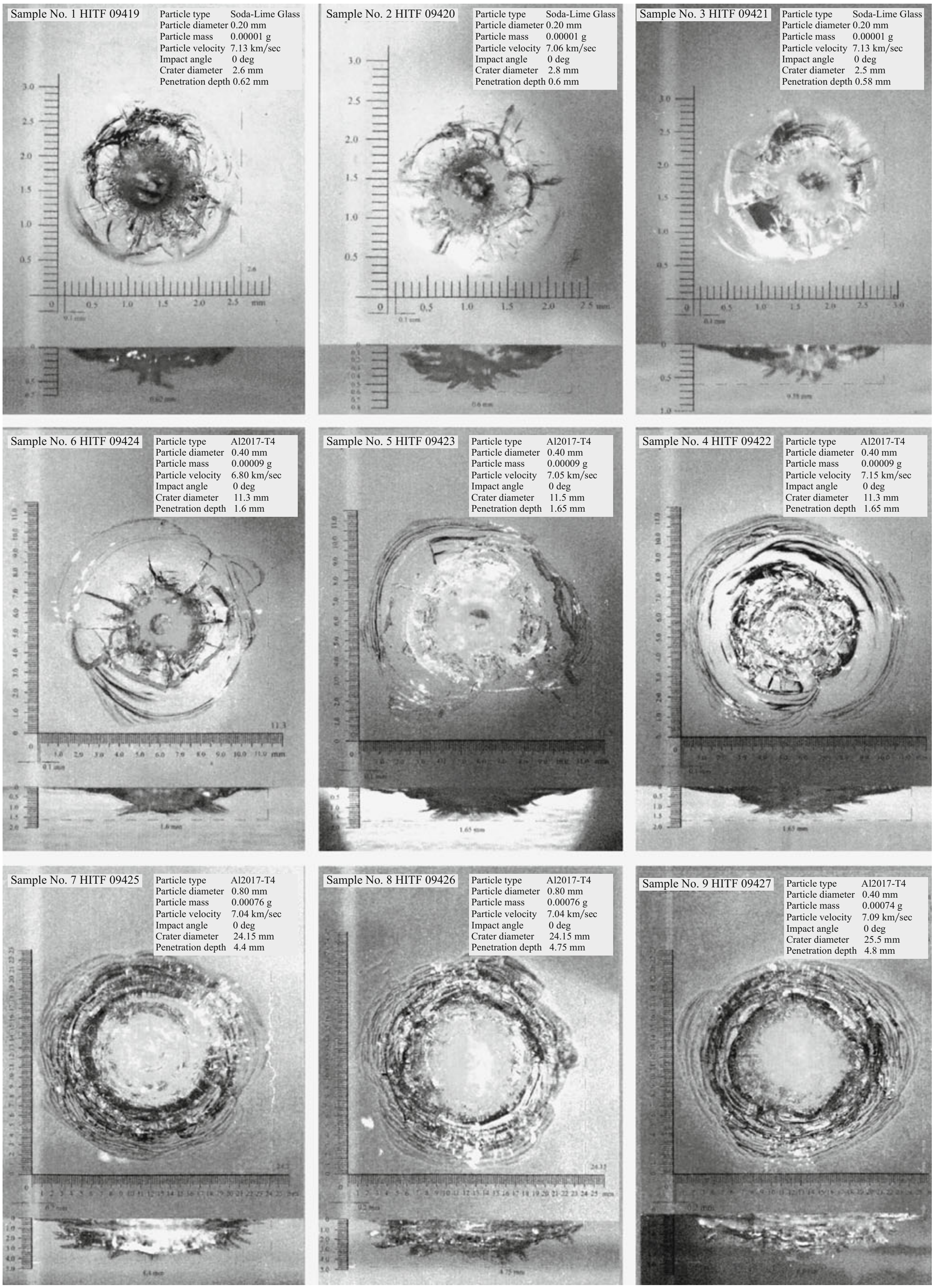

Fig. 1. Form of a defect in alkali-silicate glass impacted by particles with different diameters and $v = 6.8 – 7.15$ km/sec.

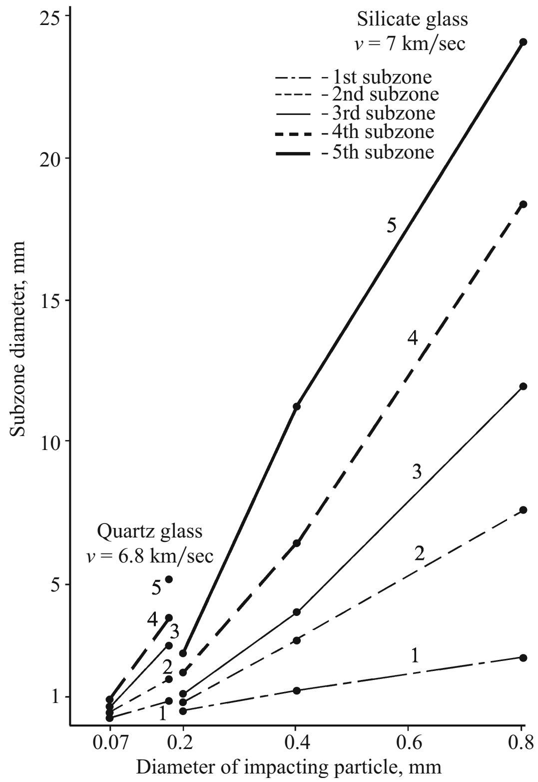

Fig. 2. Diameter of a subzone of a defect versus the impact intensity.

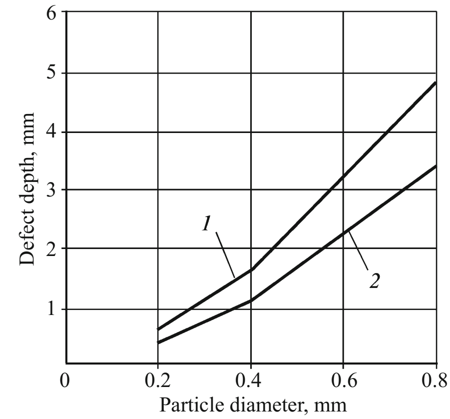

Fig. 3. Depth of defects formed in samples by particle impacts: *1*) defect with microcracks; *2*) same, no microcracks.

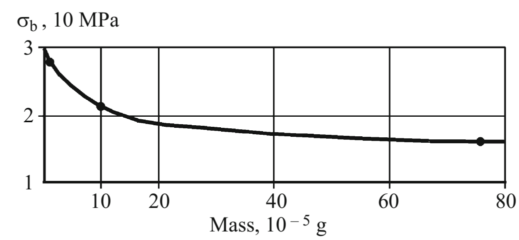

Fig. 4. Strength of silicate glasses versus the mass of the impacting particles moving with velocity v = 7 km/sec.

time of glass under a definite load irrespective of the presence of any defects in the glass — bubbles, foreign inclusions, cords and scratches, including numerous microcracks.

We strived to adapt this method to our problem without changing the crux of the approach. The construction of long-time strength curves is a laborious process which in our case consisted of three stages.

1. Testing many glass samples (at least 30) for long-time strength and constructing load – time-to-failure and load – 4th-zone diameter curves.

2. Construction of the Gaussian distribution curves for the fourth subzone diameters for different loads to determine the minimum critical diameter giving rise to glass failure.

3. Construction of the 4th-zone diameter – glass lifetime curve.

The direct measurement of the RSG gives the most reliable confirmation of the correctness of the choice of method.

TABLE 3. Depth of Defects in Samples Resulting from Particle Impacts

Sample No.	Defect depth, mm	Microcrack size, mm, in defect
1, 2, 3	0.6	0.2
4, 5, 6	1.6	0.5
7, 8, 9	4.8	1.4

The results of these tests are presented in Table 4.

The strength curve for glasses with a microparticle defect and the same impact velocity is displayed in Fig. 4. Analysis shows that the fracture resistance of the glass impacted by a microparticle must be regarded as comprised of two components. The first one is associated with the resistance of the glass directly to impact (instantaneous loss of strength) and the second with the resistance to crack growth in the glass versus the external loads (long-time strength). Evidently, the formation of defects in the initial glass substantially decreases the strength of the initial glass by more than a factor of 3 – 4, once again confirming a characteristic of glass failu-

TABLE 4. Residual Strength of Glass with Defects

Sample No.	Thickness, mm	Strength σ_b, MPa
1	15.19	24
2	15.05	28
4	14.95	22
5	14.86	22
8	15.20	16.6
9	14.90	17.4
Initial glass (12 glasses)	~14.8*	94*

* Average value.

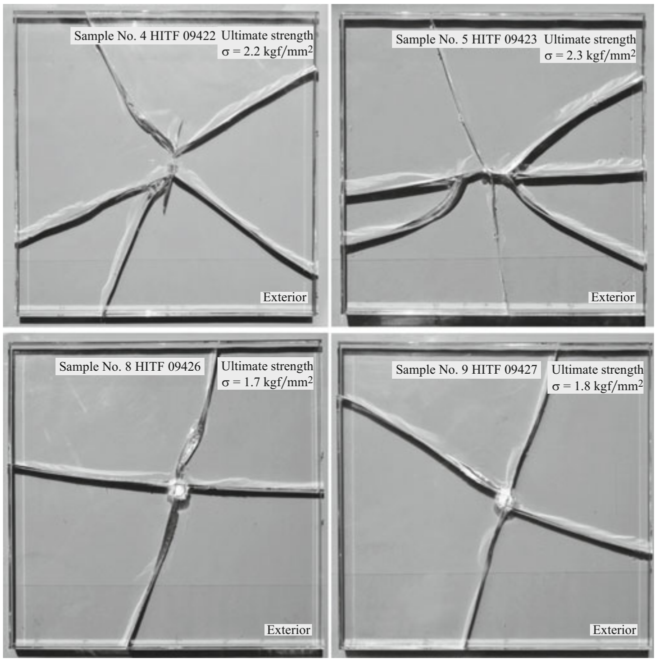

Fig. 5. Form of cracks in glass samples after tests performed by the centro-symmetric bending method: left to right, top row: sample 4, $\sigma = 22$ MPa; sample 5, $\sigma = 23$ MPa; bottom row: sample 8, $\sigma = 17$ MPa; sample 9, $\sigma = 18$ MPa.

re when a high-velocity micrometeoric particle penetrates into the glass. We attribute this kind of decrease of glass strength to the formation of large, dangerous cracks in a defect.

It is evident in the photograph of the cracks (Fig. 5) appearing during the strength testing of the samples under centro-symmetric bending that a multibranch network of cracks is formed, which indicates that cracks develop from many initial microcracks. As a rule, four cracks form under strong impacts. They are related with the specific nature of the load distribution during testing in rectangular samples with large thickness, greater than 10 mm. For centro-symmetric bending of such samples, large stresses arise at the mid-point between two sides, promoting the development of cracks in these directions. For comparative data this factor can be neglected. Round samples are needed for more accurate tests. In all cases, fracture starts at the center of a defect.

The finale of the present studies was a study of the morphology of a defect in natural quartz glass and evaluation of the RSG.

Photographs of a quartz disk magnified according to the size of the defect and the cracks in the glass after testing for RSG are presented in Fig. 6. The same sub-zone morphology of a defect is observed. It is also evident that the failure of the glass proceeds from one center with the cracks forming a fan pattern. This confirms once again the conclusion that crack development in round samples is determined by the presence of numerous microcracks and by the shape of the samples.

The RSG testing of quartz glass showed that the RSG is $\sigma = 19.8$ MPa, which is a factor of 2.5 – 3 times lower than the defect-free strength of the initial quartz glass, which we predicted.

The data obtained show the following:

1) the scale factor with respect to thickness and area of the glass plates impacted by a micrometeorite particle has no effect on the size and character of the defects. The strength is observed to drop by a factor of 2 or more for $100 \times 100 \times 5$ mm and $300 \times 300 \times 15$ mm glass with diameter 254×14 mm;

2) the mechanism of defect formation and the defect morphology for impact by high-velocity particles are the same for glasses with different composition;

3) the regularities determined in this work and suitably adjusted can be applied to glasses of any chemical composition, including for quartz glasses.

CONCLUSIONS

These studies were the next step to reaching the main objective — assessment of the danger of defects in portholes during use. In the subsequent long-time strength curves will be constructed for glass with defects using the method deve-

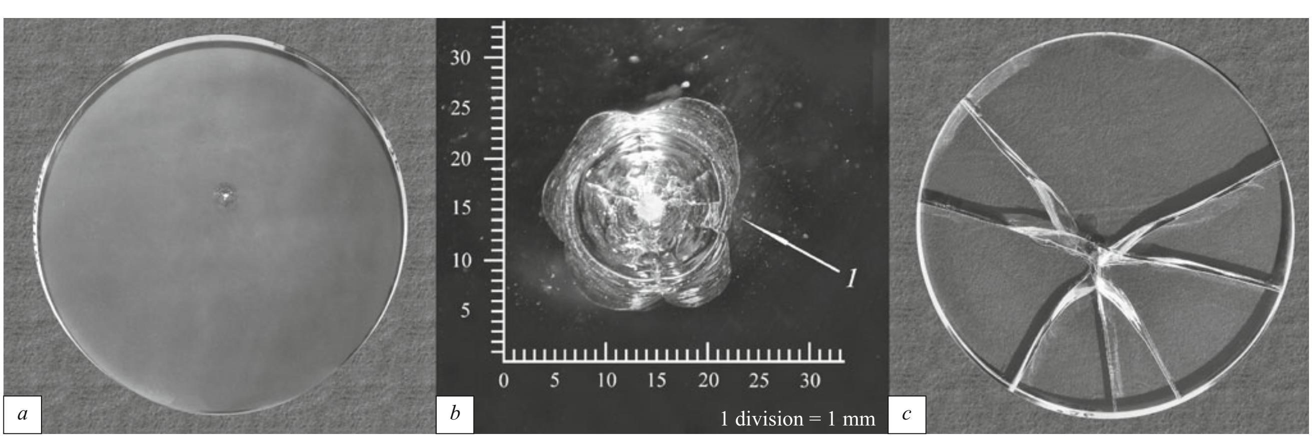

Fig. 6. Quartz disks before tests (*a*), defects (*b*) and post-test form of a crack (*c*).

loped at NIITS. The operational lifetime of glass can be predicted and precautionary measures for increasing the operational reliability of portholes in space can be developed only after these curves have been constructed using the morphology and size of a defect in the 4th zone.

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